
I FOUND THE HUGS BISON.
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Precision calculations in the Higgs sector of the complex MSSM: Towards the LC precision

Sven Heinemeyer, IFCA/IFT (CSIC, Santander/Madrid)

Whistler, 11/2015

1. The Grand Scheme
2. Renormalizing the MSSM
3. Results for the MSSM Higgs at the LC
4. Conclusions

1. The Grand Scheme

The LHC up and running . . .
→ discovery of BSM physics in 2016?

The ILC (and CLIC?) still coming . . .
. . . a bit later than anticipated
→ to investigate BSM physics

⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the (N)MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities . . .)

In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

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In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

$\Rightarrow$ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^\pm_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ for obvious reasons some focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Where are we? (a selection!)

1. Neutral Higgs boson masses
   - $\mathcal{O}(\alpha_t\alpha_s)$ in the cMSSM [S.H., W. Hollik, H. Rzehak, G. Weiglein '07]
   - $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, $\mathcal{O}\left(\alpha_t^2\alpha_s\right)$, rMSSM [S. Martin '07]
   - $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, rMSSM (incl. fin. terms) [Haarlander, Kant, Mihaila, Steinhauser '08]
   - log-resummation, 2L/3L [Hahn et al. '13][Draper et al. '13][E. Bagnaschi et al. '14] [J. Pardo Vega et al. '14][Lee et al. '15]
2. Charged Higgs mass
   - 1-loop [M. Frank et al. '06] $\mathcal{O}(\alpha_t\alpha_s)$ [M. Frank et al. '13] $\mathcal{O}\left(\alpha_t^2\right)$ [Hollik, Passehr '14]
3. Production cross sections at the LC
   - $e^+e^- \to h_ih_j, Zh_i, \gamma h_i$, full one-looop, cMSSM [S.H., C. Schappacher '15]
   - $e^+e^- \to H^\pm e^\mp \nu$ at one-loop, rMSSM [O. Brein, T. Figy '07][T. Farris et al. '04]
   - Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
4. Higgs decays
   - full 1-loop (depending on final state) [. . .]
   - Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
5. Decays to Higgs bosons
   - full 1-loop, cMSSM [K. Williams et al. '11][S.H., C. Schappacher '14, 15] [A. Bharucha, T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacer '11 - '13]

What is missing? (a selection!)

1. Neutral Higgs boson masses
   - full 2-loop
   - more 3-loop (and in “easier accessible” scheme?)
   - leading 4-loop
   - Improved combinatin of LL, NLL, . . . resummation with diag. calc.
2. Charged Higgs boson mass
   - (sub)leading 2-loop
3. Higgs bosons production
   - full 1-loop in the cMSSM (some initial states)
   - leading 2-loop
4. Higgs decays
   - full 1-loop in the r/cMSSM (some final states)
   - leading 2-loop
5. Decays to Higgs bosons probably ok now

$\Rightarrow$ provide corresponding codes!

2. Renormalization of the cMSSM

Generic problems for SUSY loop calculations:

- SUSY has to be preserved in the calculation
- Many different mass scales
- Many more mass scales than free parameters
- Even more parameters: mixing angles, complex phases
- Renormalization is much more involved than in the SM
  - much less explored than in the SM
  - has to preserve/respect mass relations
  - depend on mass scales realized in Nature
  - sometimes no really good solution exist (e.g. $\tan\beta$)
  - many sectors enter at the same time

  $\Rightarrow$ this is the biggest issue!

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V = &\; m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ & + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2 \end{aligned}$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}
\end{aligned}
$$

$$
\begin{aligned}
V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&\quad + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2
\end{aligned}
$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$
\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2
$$

The Higgs sector of the cMSSM at tree-level:

- phase of m_{12} :

  $m_{12} = 0$ and $\mu = 0 \Rightarrow$ additional $U(1)$ (PQ) symmetry

  reality: $m_{12} \neq 0$, $\mu \neq 0$

  $\Rightarrow$ perform PQ transformation with ϕ_{PQ}

$$\begin{aligned} m_{12}^{2\prime} &= |m_{12}^2| e^{i(\phi_{m_{12}} - \phi_{\text{PQ}})} \\ \mu' &= |\mu| e^{i(\phi_\mu - \phi_{\text{PQ}})} \end{aligned}$$

  $\Rightarrow$ m_{12} can always be chosen real

- phase of H_2: ξ :

  mixing between $\mathcal{CP}$-even and $\mathcal{CP}$-odd states:

$$\mathcal{M}_{\mathcal{CP}-\text{even},\mathcal{CP}-\text{odd}} = \begin{pmatrix} 0 & m_{12}^2 \sin\xi \\ -m_{12}^2 \sin\xi & 0 \end{pmatrix}$$

  Tadpoles have to vanish: $T_A^{\text{tree}} \propto \sin\xi\, m_{12}^2 \overset{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ no $\mathcal{CP}$V at tree-level

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot\beta, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$$m^2_{\tilde{t}_{1,2}} = m_t^2 + \frac{1}{2}\left(M^2_{\tilde{t}_L} + M^2_{\tilde{t}_R} \mp \sqrt{(M^2_{\tilde{t}_L} - M^2_{\tilde{t}_R})^2 + 4m_t^2|X_t|^2}\right)$$

$\Rightarrow$ independent of ϕ_{X_t}

but $\theta_{\tilde{t}}$ is now complex

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$ $\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

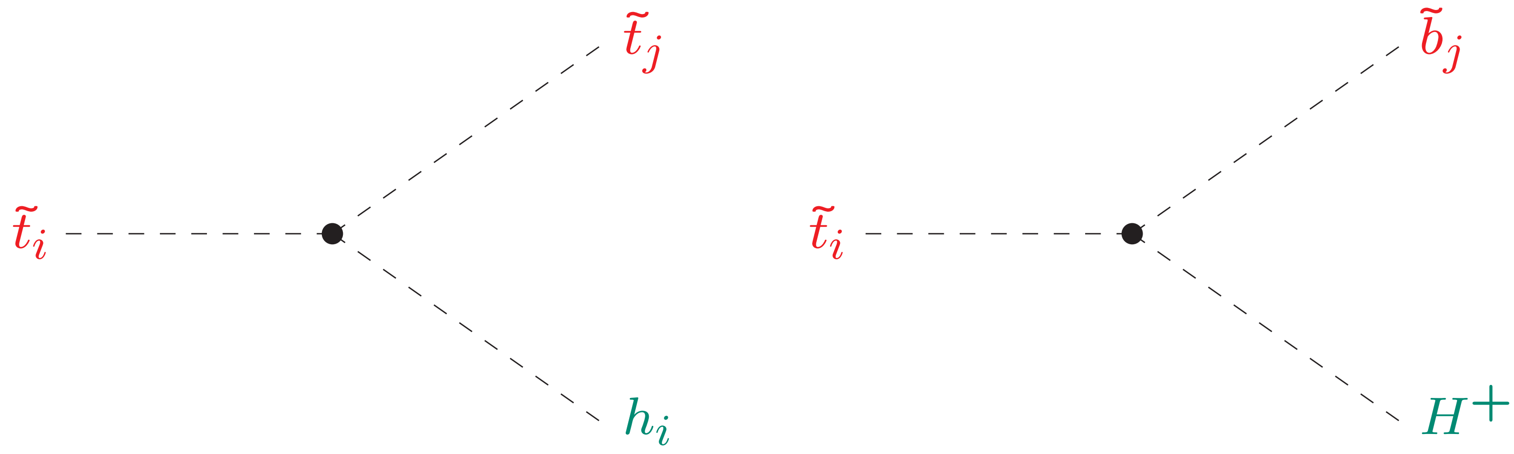
$\Rightarrow$ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

Examples for processes with (external) stops and Higgs bosons:



– important decay modes of stops
– A_t and A_b directly enter the vertex
– possible source of Higgs bosons at the LHC/ILC
– ...

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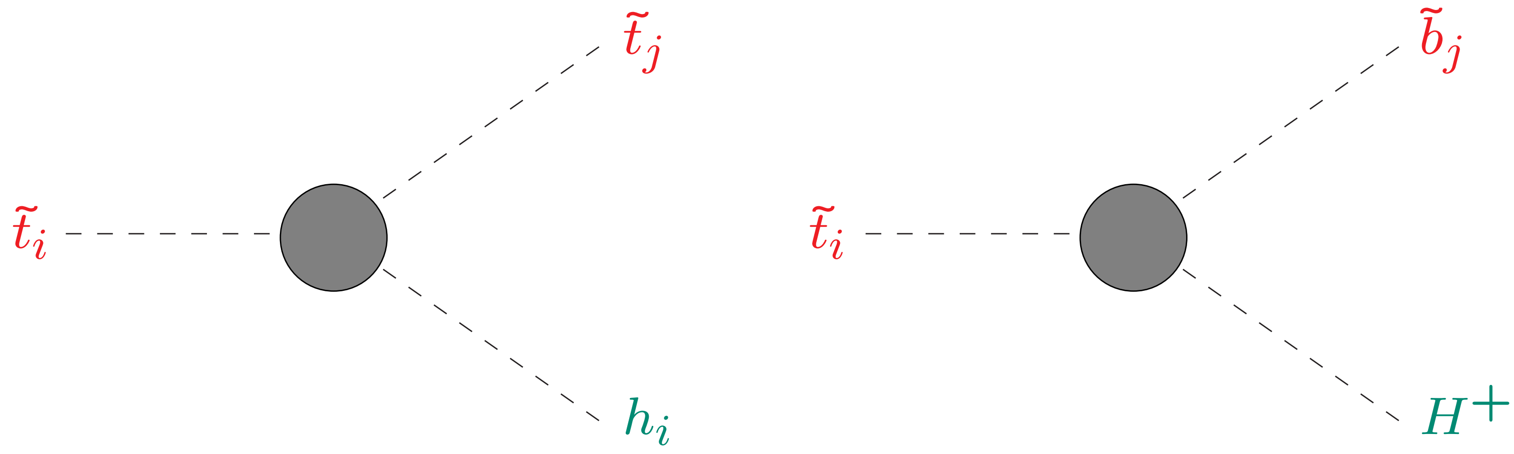

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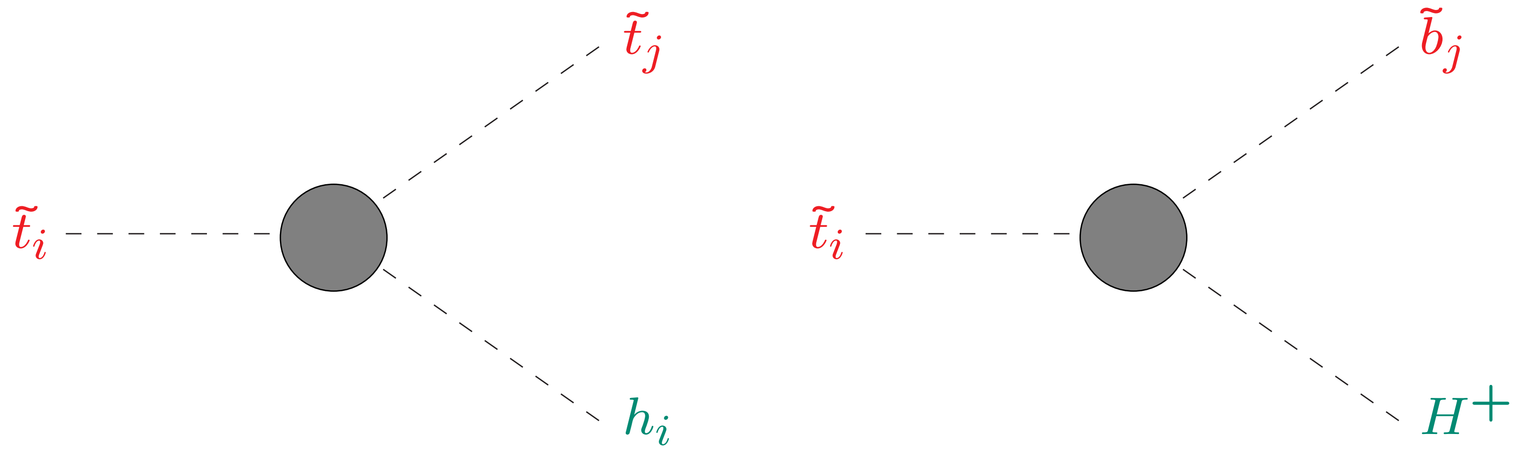

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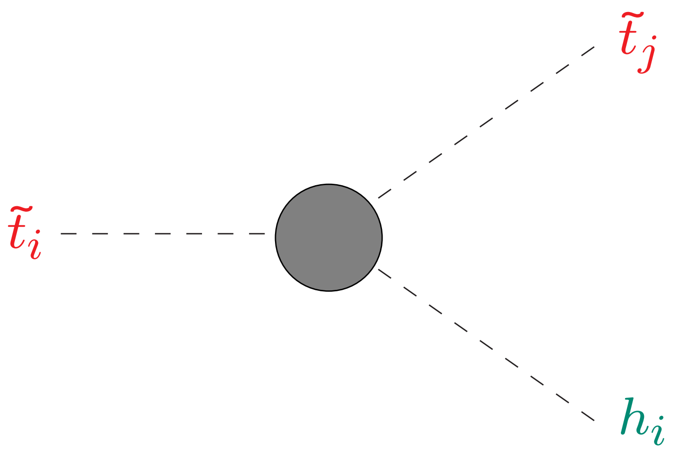

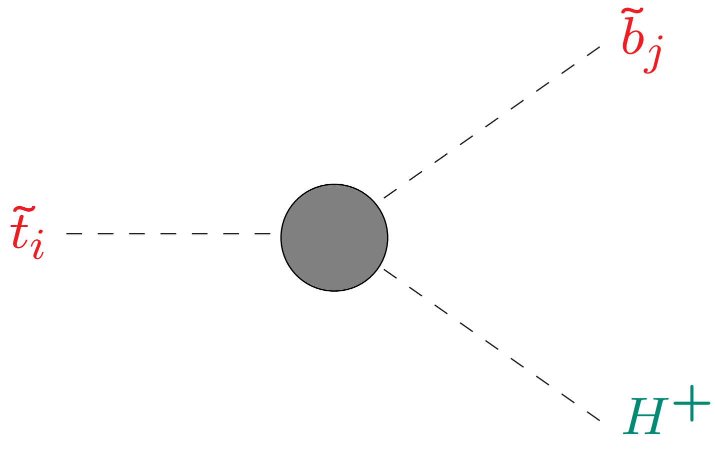

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⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!

⇒ with on-shell properties for external particles!

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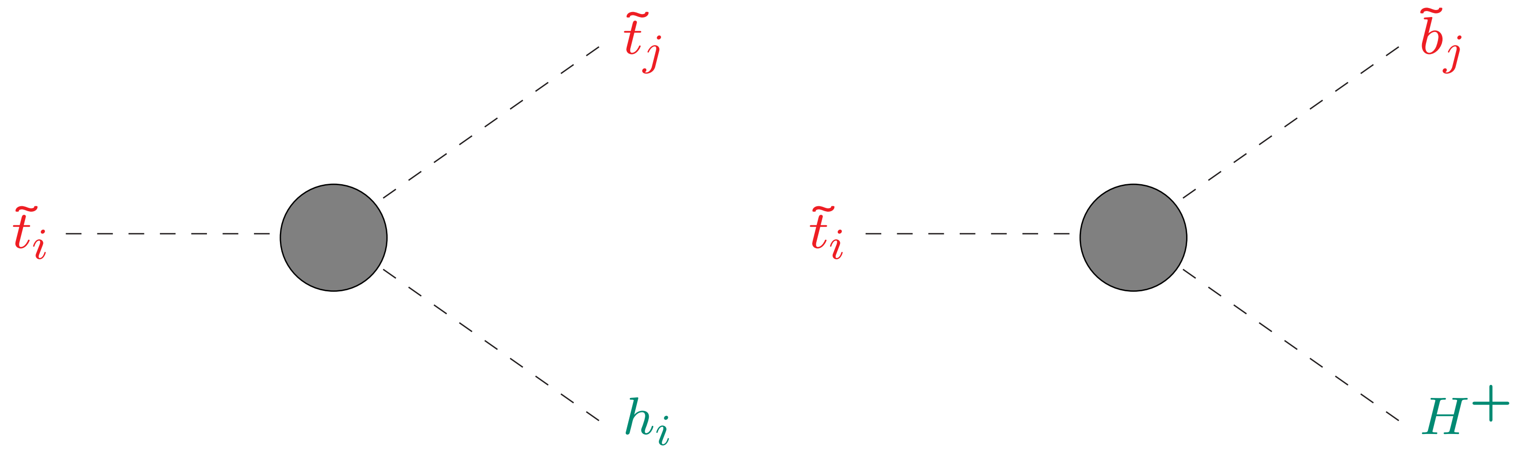

– important decay modes of stops

– A_t and A_b directly enter the vertex incl. complex phases!

– possible source of Higgs bosons at the LHC/ILC

– . . .

⇒ higher-order corrections important!

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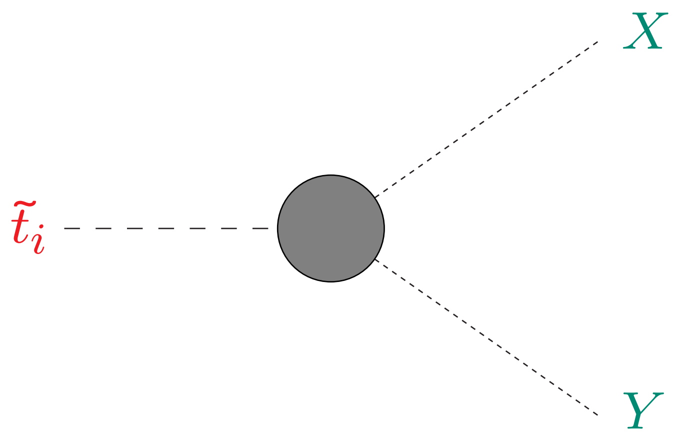
⇒ including complex phases!

The bigger picture: stop decays in the cMSSM



$\Rightarrow$ to get BRs right $\Rightarrow$ all decays needed

$\Rightarrow$ (nearly) all sectors of the cMSSM enter as external particles

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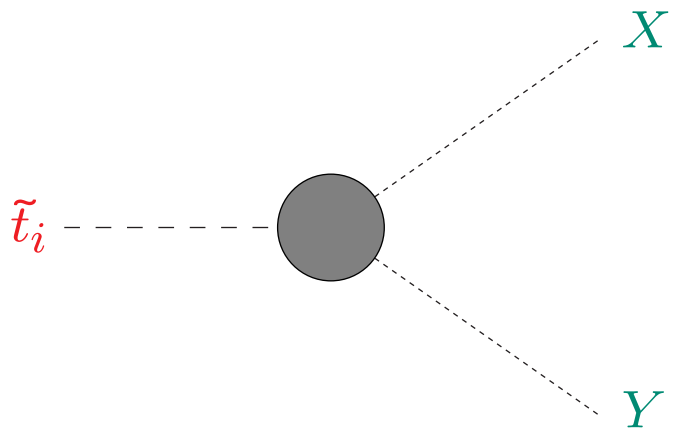

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Available for LC precision: cMSSM full one-loop:

– SUSY decays to Higgs
– Higgs decays to SM fermions, Higgs Higgs
– Higgs decays to SUSY particles
– $e^+e^- \to h_i h_j, Zh_i, \gamma h_i$

LC potential:

The clean environment of the ILC would permit a detailed study of the SUSY decays

The ILC environment would result in an accuracy of the relative branching ratio

$$\mathrm{BR}^{\mathrm{full}} \equiv \frac{\Gamma^{\mathrm{full\ 1L}}(\mathrm{SUSY} \to \mathrm{xy})}{\Gamma^{\mathrm{full\ 1L}}_{\mathrm{tot}}}$$

$$\frac{\delta\mathrm{BR}}{\mathrm{BR}} \equiv \frac{\mathrm{BR}^{\mathrm{full}} - \mathrm{BR}^{\mathrm{tree}}}{\mathrm{BR}^{\mathrm{full}}}$$

close to the statistical uncertainty

$\Rightarrow$ Precision at the per-cent level possible!

$\Rightarrow$ theory precision at the per-cent level required!

Renormalization status:

– LC precision requires all calculations at the per-cent level

– full complex MSSM renormalized

[A. Bharucha, T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '13]

– stable and well behaved results over nearly complete parameter space

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$\Rightarrow$ and so we did :-)

3. Results for the MSSM Higgs at the LC

A. Status and latest results for M_h prediction
$\Rightarrow$ still far away from LC precision!

B. Status for the charged Higgs boson mass predictions

C. Status of $e^+e^- \to h_i h_j, Zh_i, \gamma h_i$
$\Rightarrow$ see talk by S.H. yesterday :-)

D. Recent results for Higgs boson decays

E. Recent results for decays to Higgs bosons

3A/B) MSSM Higgs mass prediction: The embarrasing situation

The light $\mathcal{CP}$-even Higgs mass accuracy in the MSSM:

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Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV
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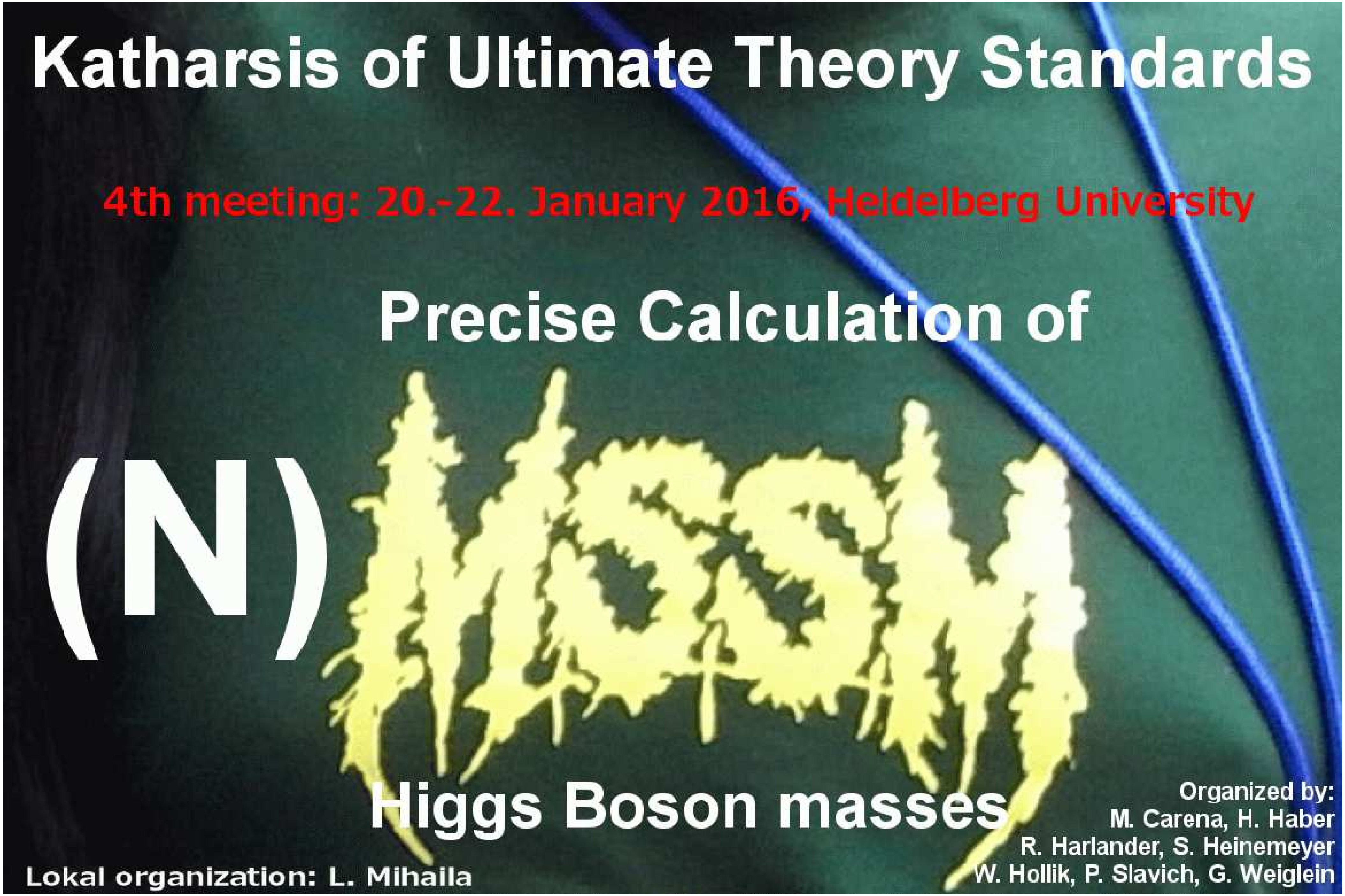
$\Rightarrow$ dedicated working group has been formed to take care . . . (KUTS)


Katharsis of Ultimate Theory Standards
4th meeting: 20.-22. January 2016, Heidelberg University
Precise Calculation of
(N)
Higgs Boson masses
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein
Lokal organization: L. Mihaila

3D) Higgs to SUSY decays

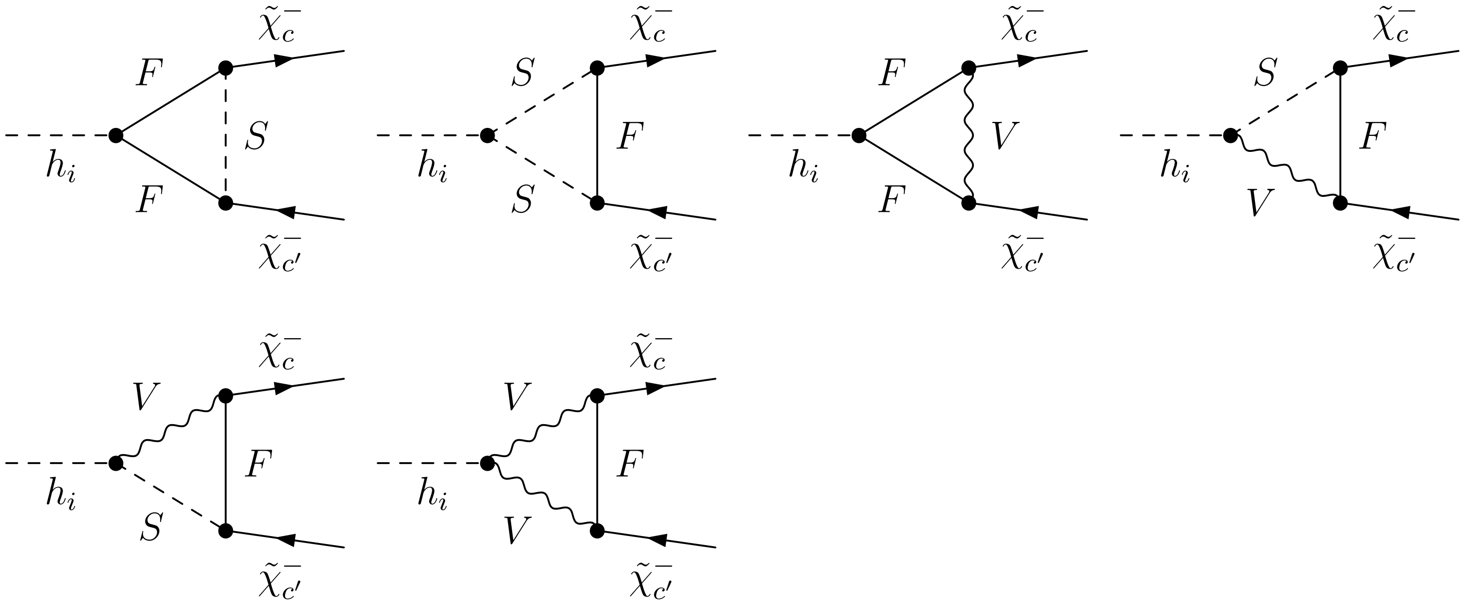
3D-1) Higgs decays to charginos/neutralinos

[arXiv:1503.02996]

$$\Gamma(h_i \to \tilde{\chi}_c^- \tilde{\chi}_{c'}^+) \quad (i = 1, 2, 3;\ c, c' = 1, 2)$$

$$\Gamma(h_i \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0) \quad (i = 1, 2, 3;\ n, n' = 1, 2, 3, 4)$$

$$\Gamma(H^\pm \to \tilde{\chi}_n^0 \tilde{\chi}_c^\pm) \quad (n = 1, 2, 3, 4;\ c = 1, 2)$$



Numerical example scenario:

$\tan\beta$	μ	A_{u_g}	A_{d_g}	A_{e_g}	$\lvert M_1\rvert$	M_2	M_3	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_1}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

Parameters varied: $M_{H^\pm}$, M_1, φ_{M_1}

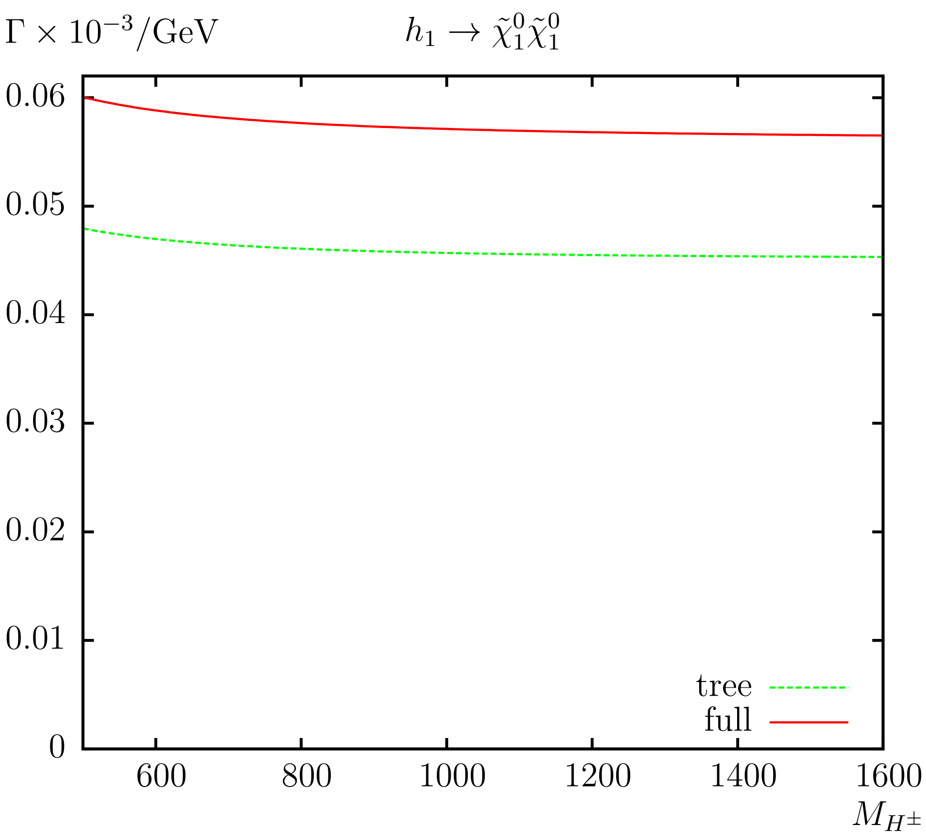
– in agreement with exp. data

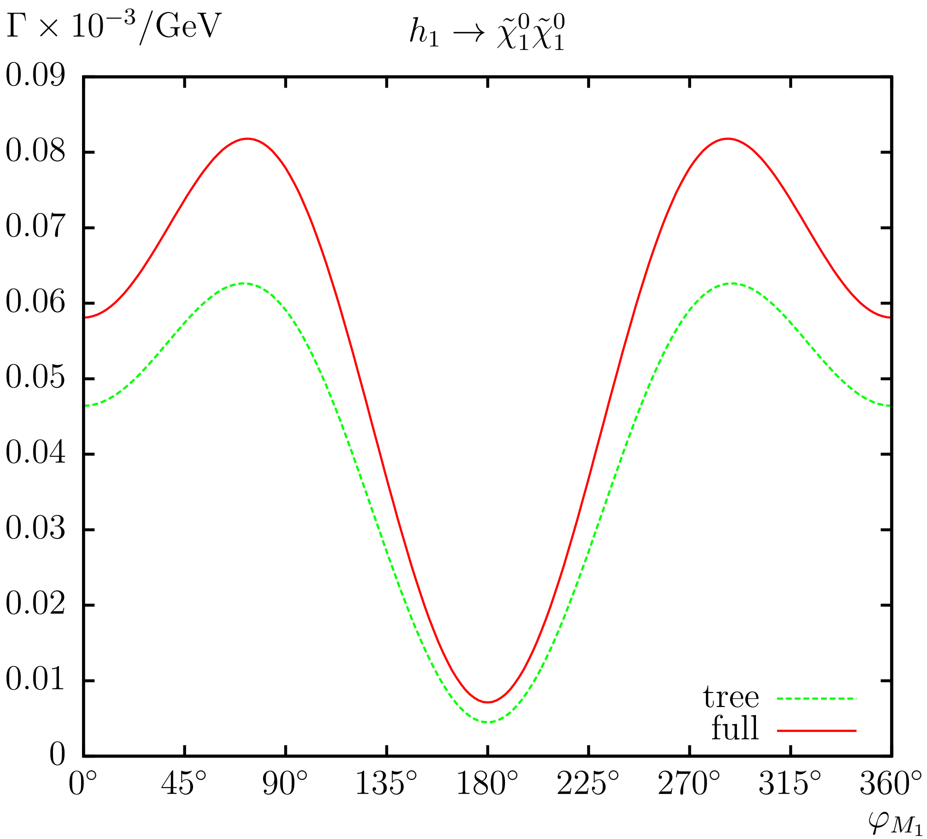
– opens up many (all) decay channels

– relevant parameters varied

– ...

Light Higgs decay to Dark Matter (I):

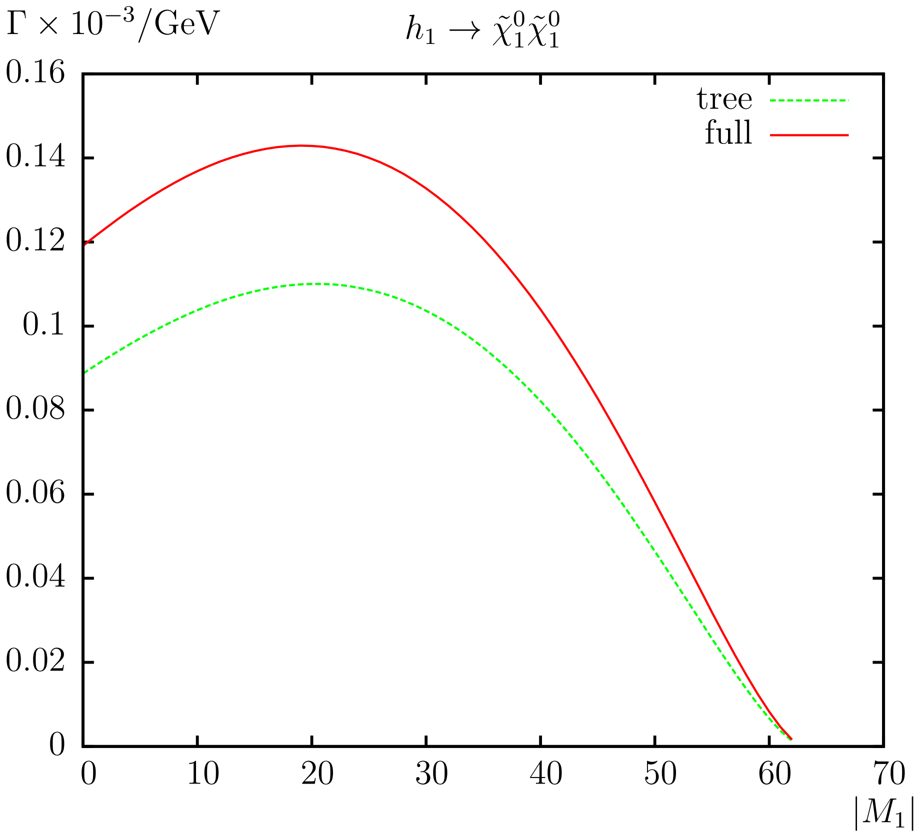


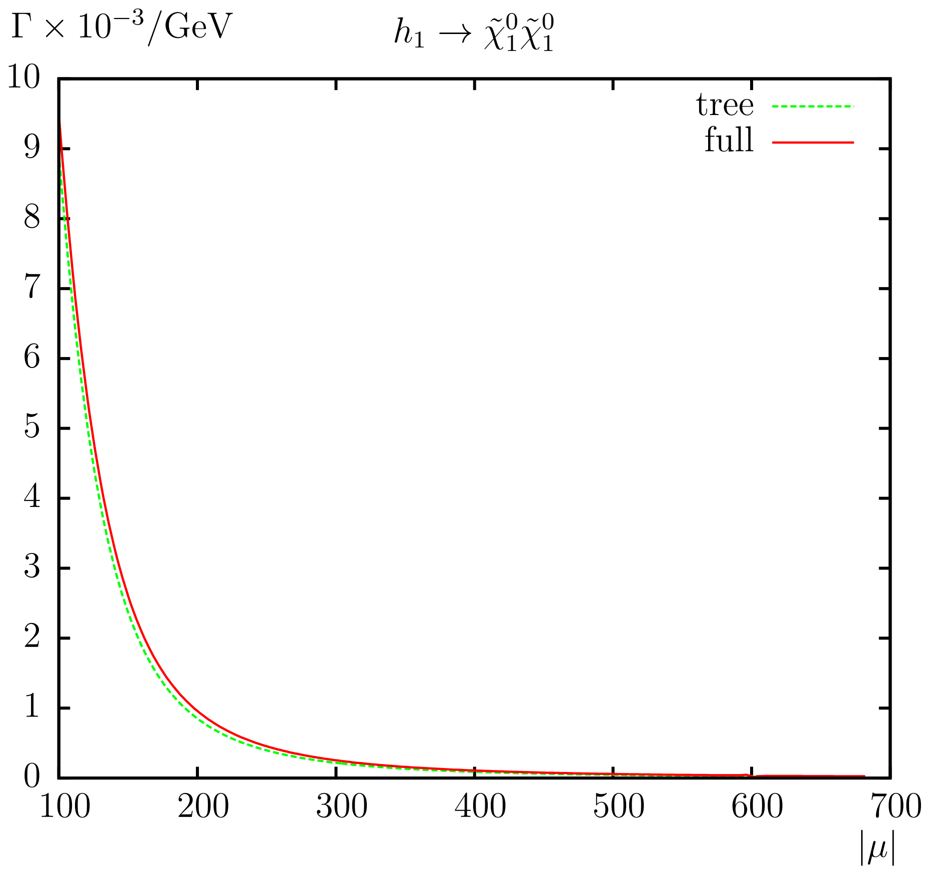


$\Rightarrow$ loop corrections $\sim$ 20%

$\Rightarrow$ strong phase dependence

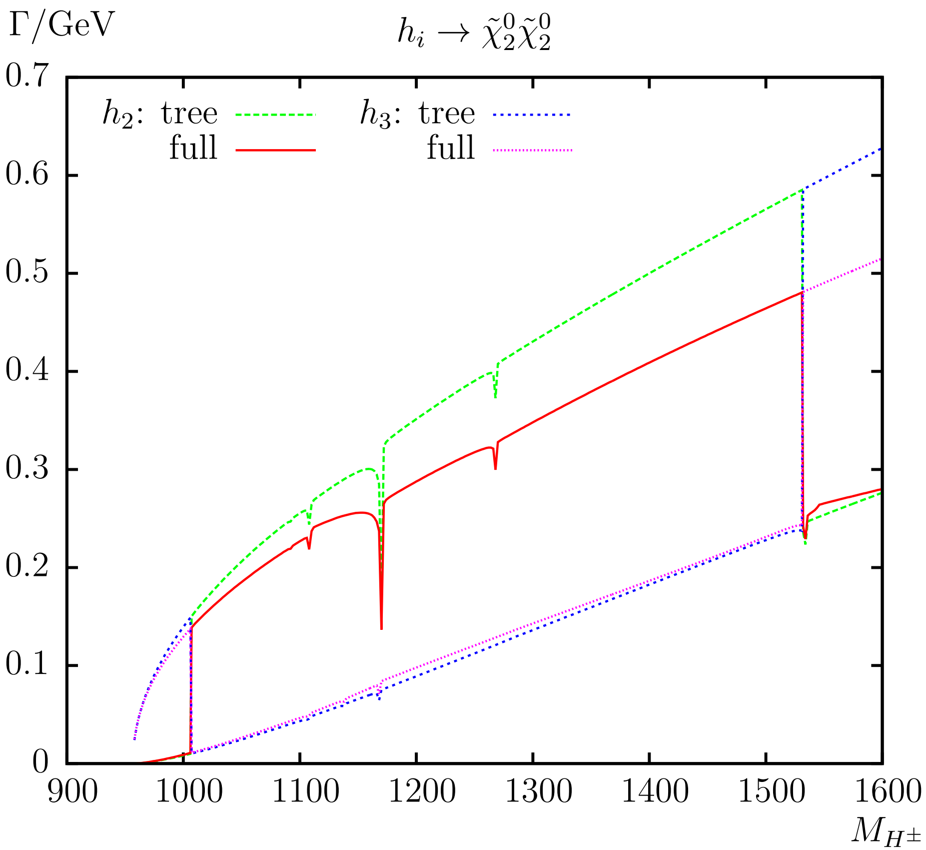
Light Higgs decay to Dark Matter (II):

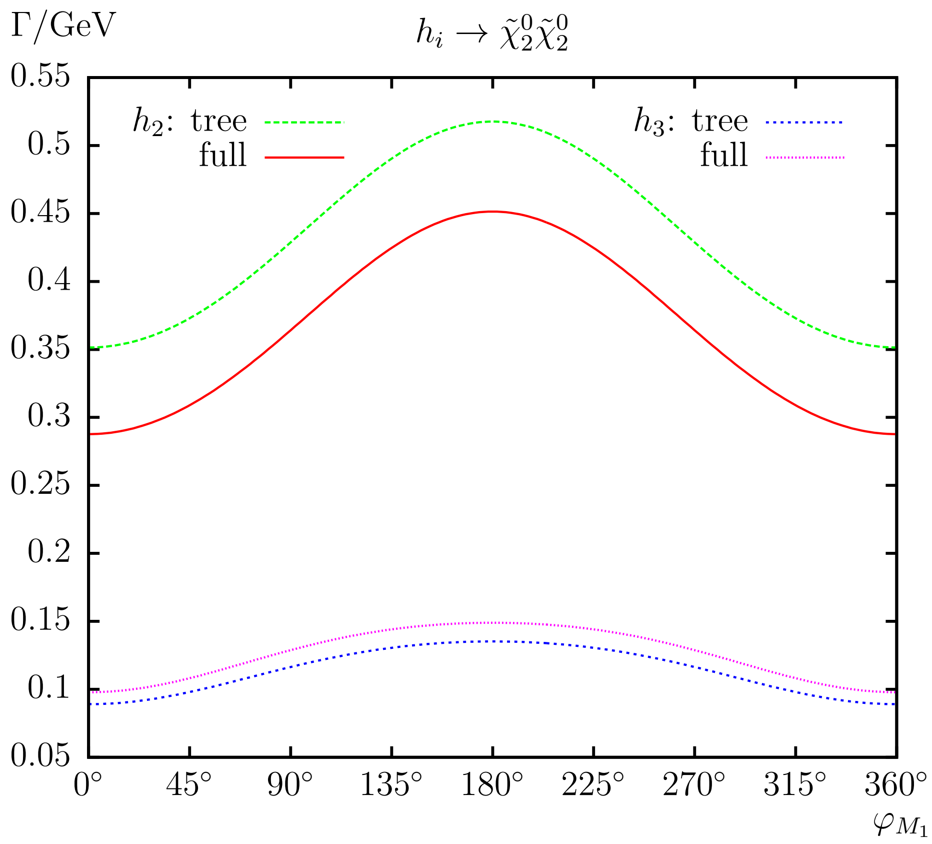




$\Rightarrow$ strong dependence on $|M_1|$, μ

Heavy Higgs decay to heavier neutralinos:



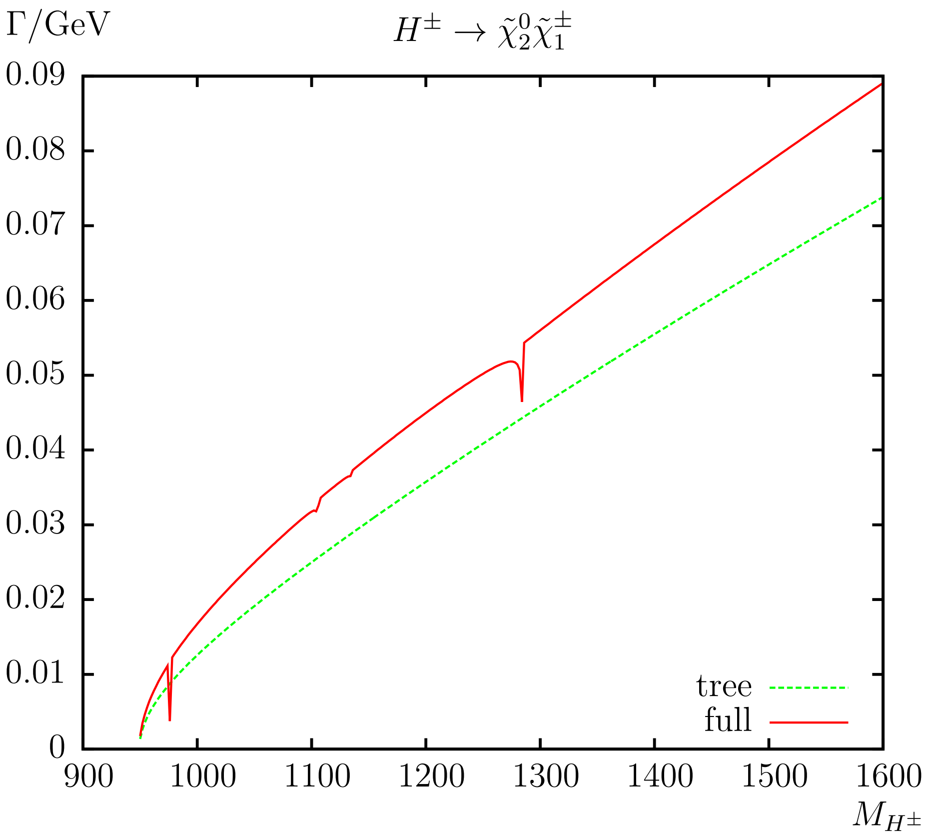


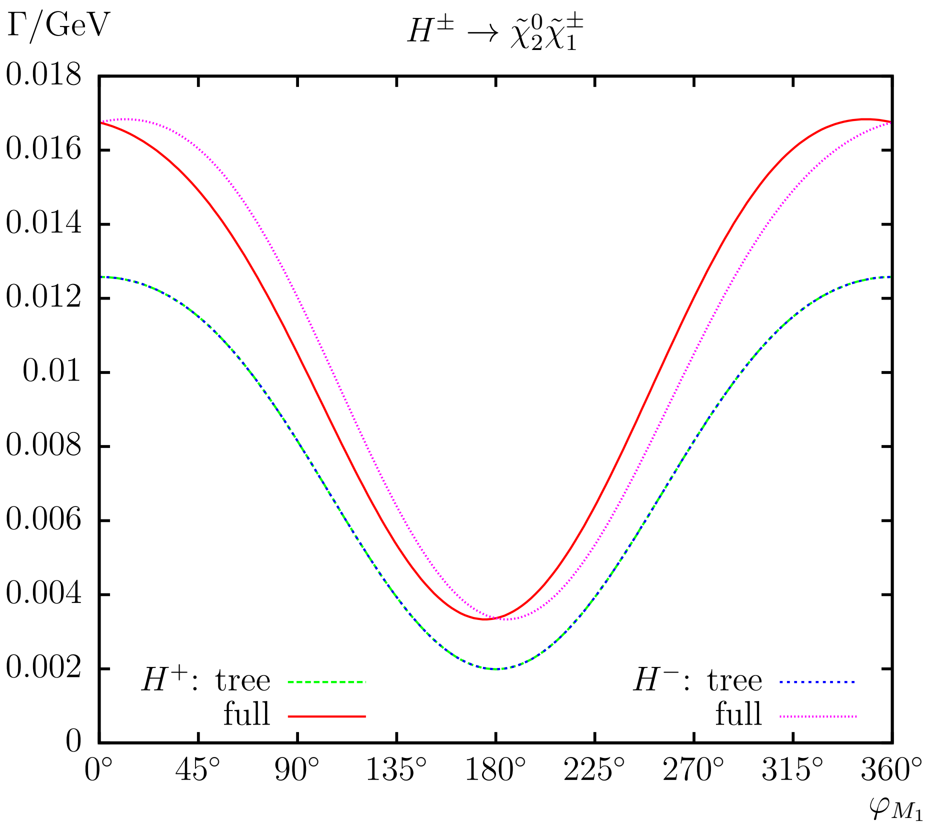
$\Rightarrow$ loop corrections up to $\sim$ 20%

$\Rightarrow$ strong phase dependence

$\Rightarrow$ level crossing, thresholds, . . .

Charged Higgs decay:





⇒ loop corrections up to $\sim 20\%$

⇒ strong phase dependence

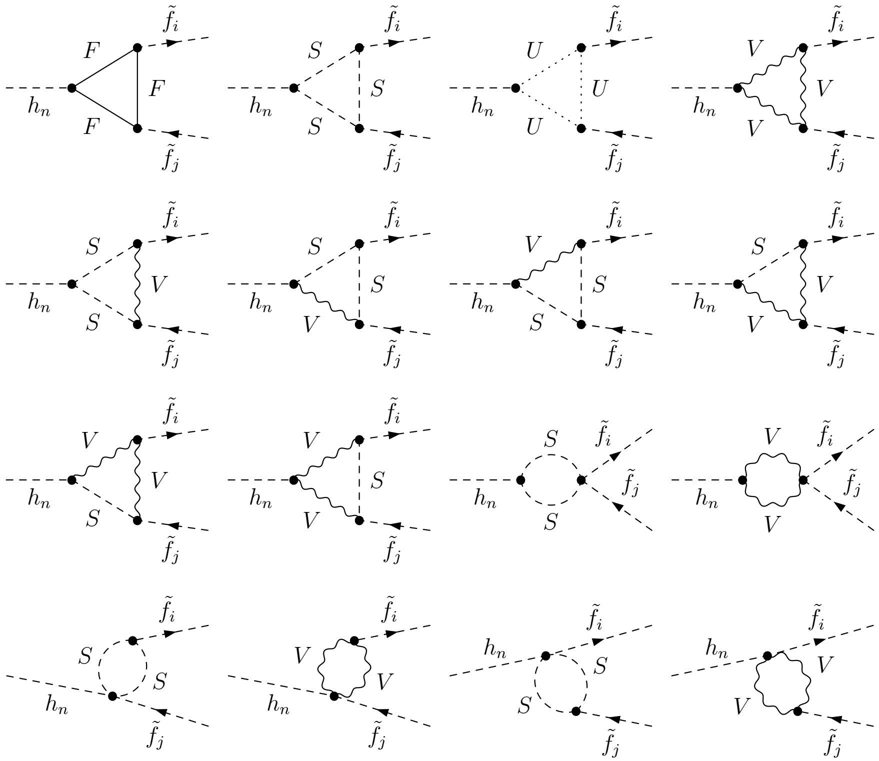
⇒ small difference between H^+ and H^- decay

3D-2) Higgs decays to sfermions

[arXiv:1410.2787]

$$\Gamma(h_n \to \tilde{f}_i \tilde{f}_j^\dagger) \quad (n = 2, 3;\ i, j = 1, 2)$$

$$\Gamma(H^\pm \to \tilde{f}_i \tilde{f}_j'^\dagger) \quad (i, j = 1, 2)$$



Numerical example scenario:

$\tan\beta$	μ	$\lvert A_t \rvert$	$\lvert A_b \rvert$	$\lvert A_\tau \rvert$	M_1	M_2	M_3	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_2}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

Parameters varied: $M_{H^\pm}$, ϕ_{A_t}, ϕ_{A_b}, ϕ_{A_τ}

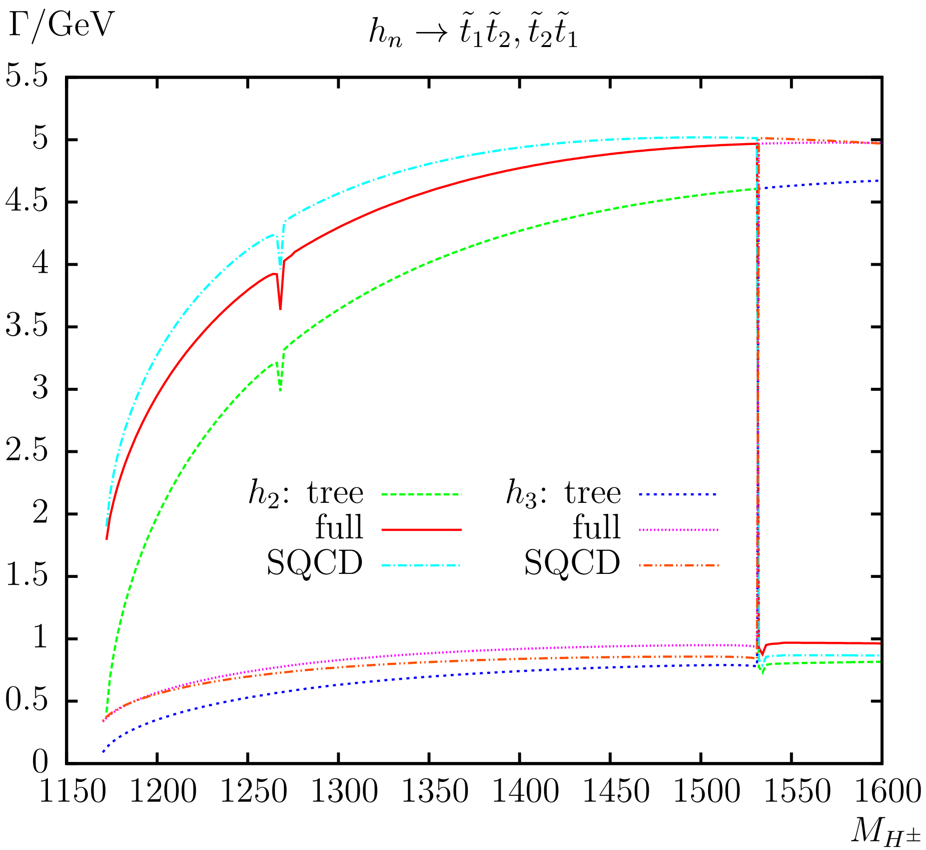
– in agreement with exp. data

– opens up many (all) decay channels

– relevant parameters varied

– ...

Heavy Higgs decay to stops:

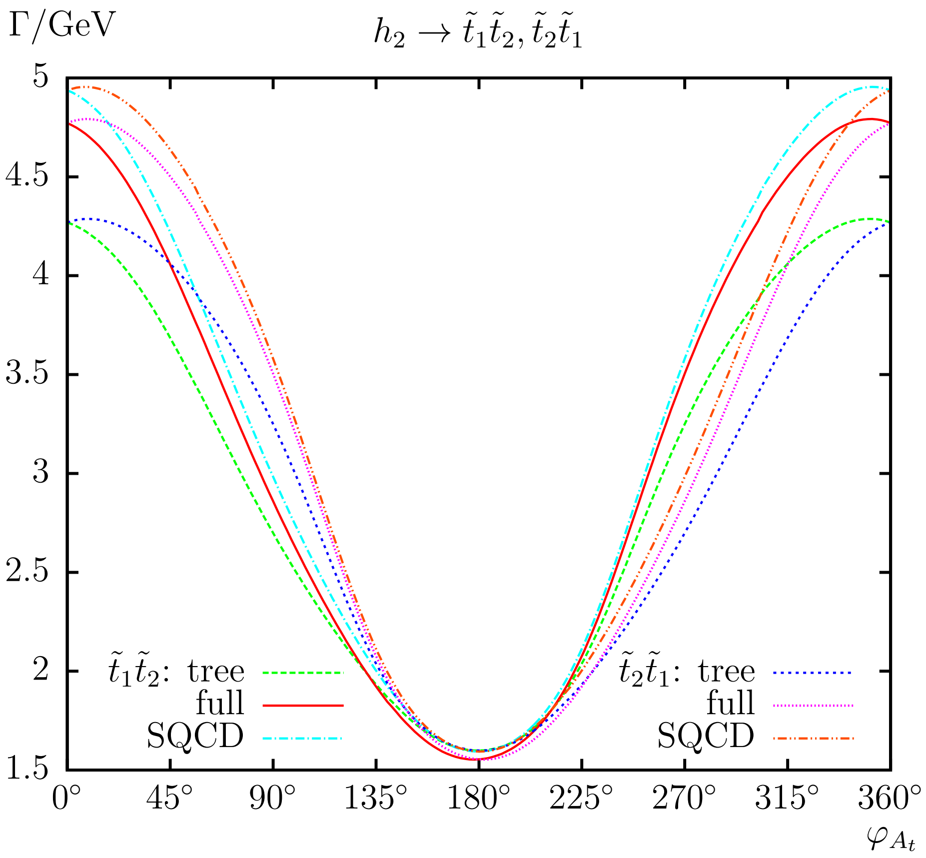


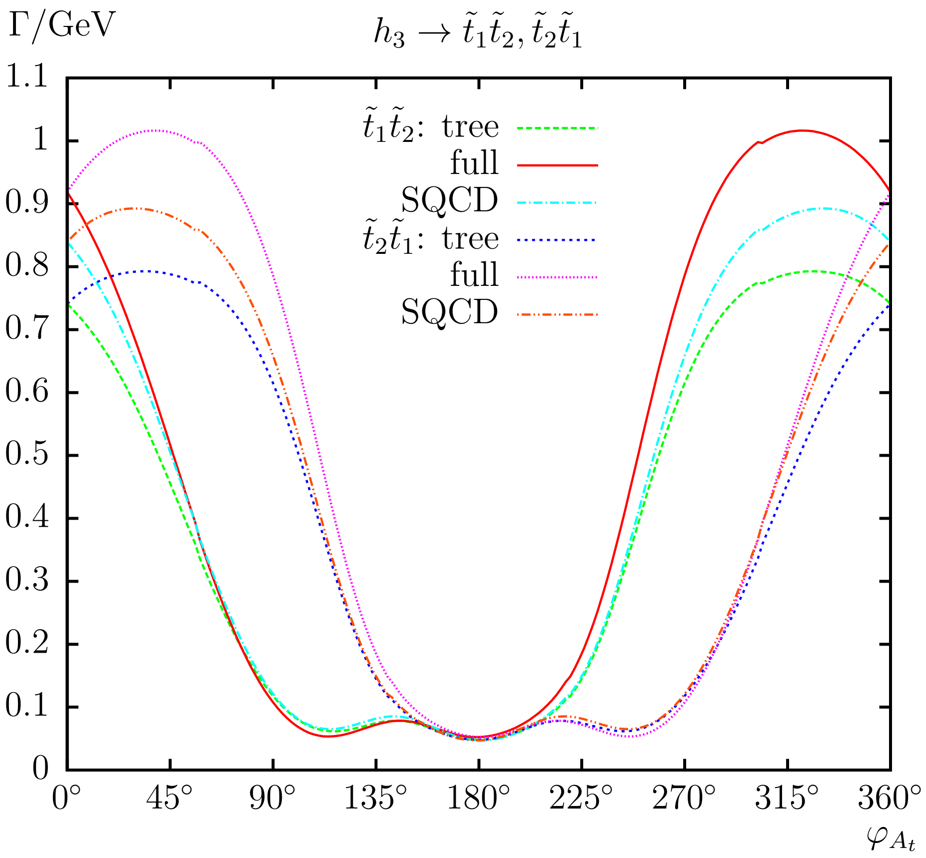
⇒ loop corrections up to ∼ 30%

⇒ SUSY QCD not sufficient

⇒ level crossing, thresholds, . . .

Heavy Higgs decay to stops:



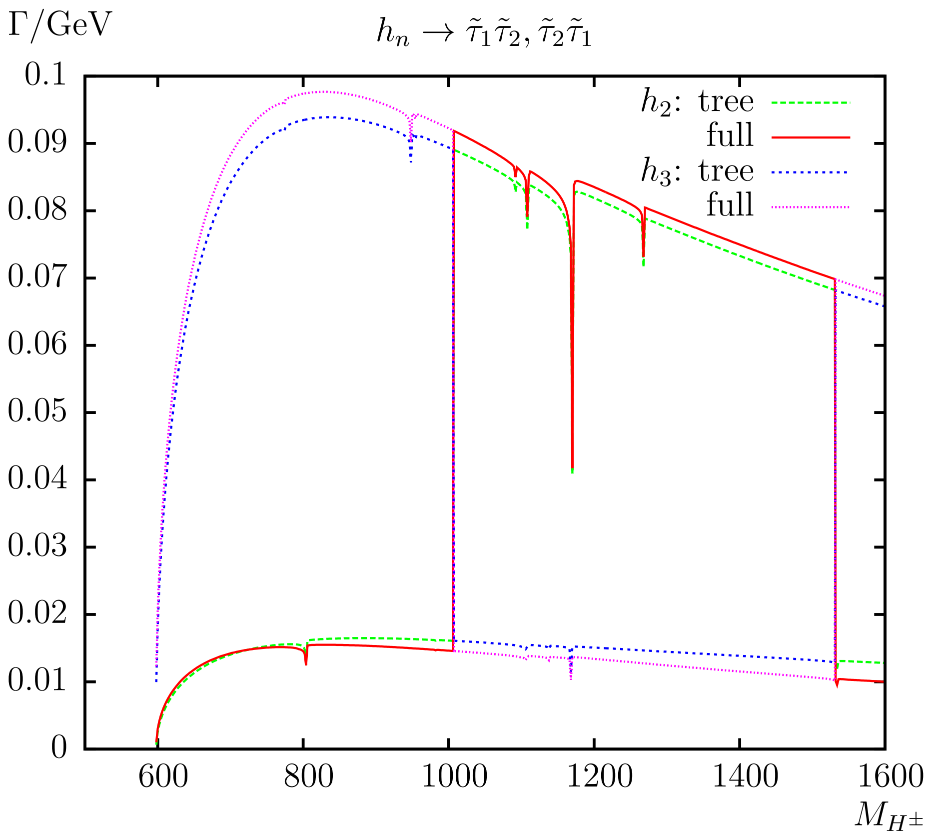


$\Rightarrow$ loop corrections up to $\sim 30\%$, SUSY EW important

$\Rightarrow$ strong phase dependence

$\Rightarrow$ difference between charge conjugated decays

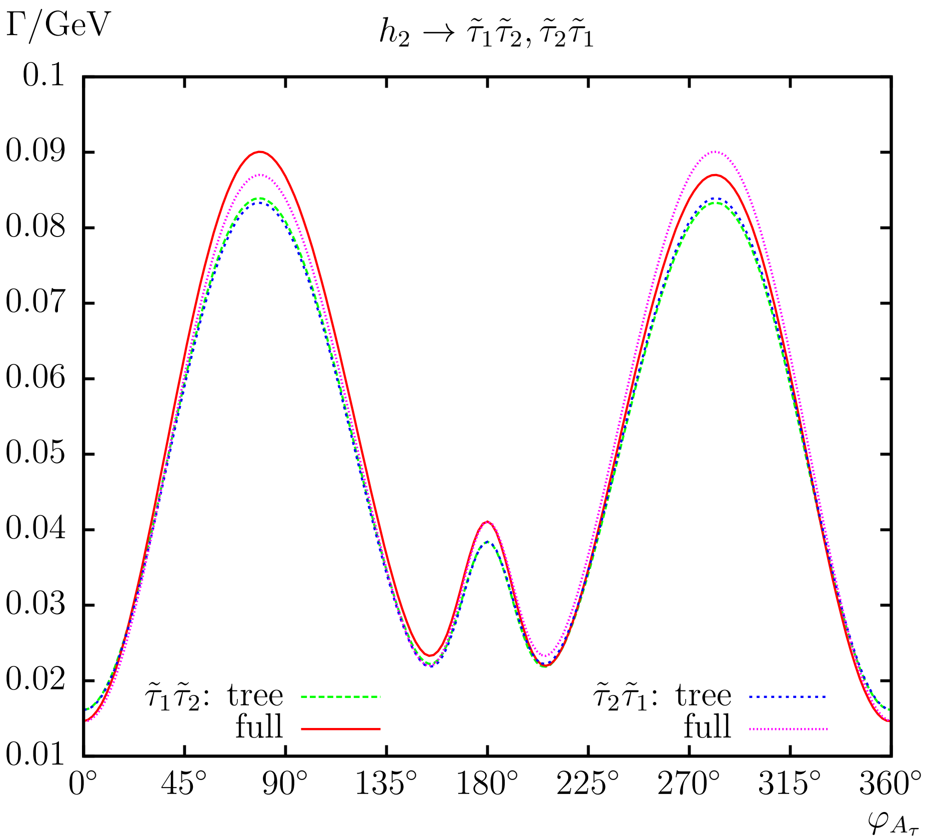
Heavy Higgs decay to staus:

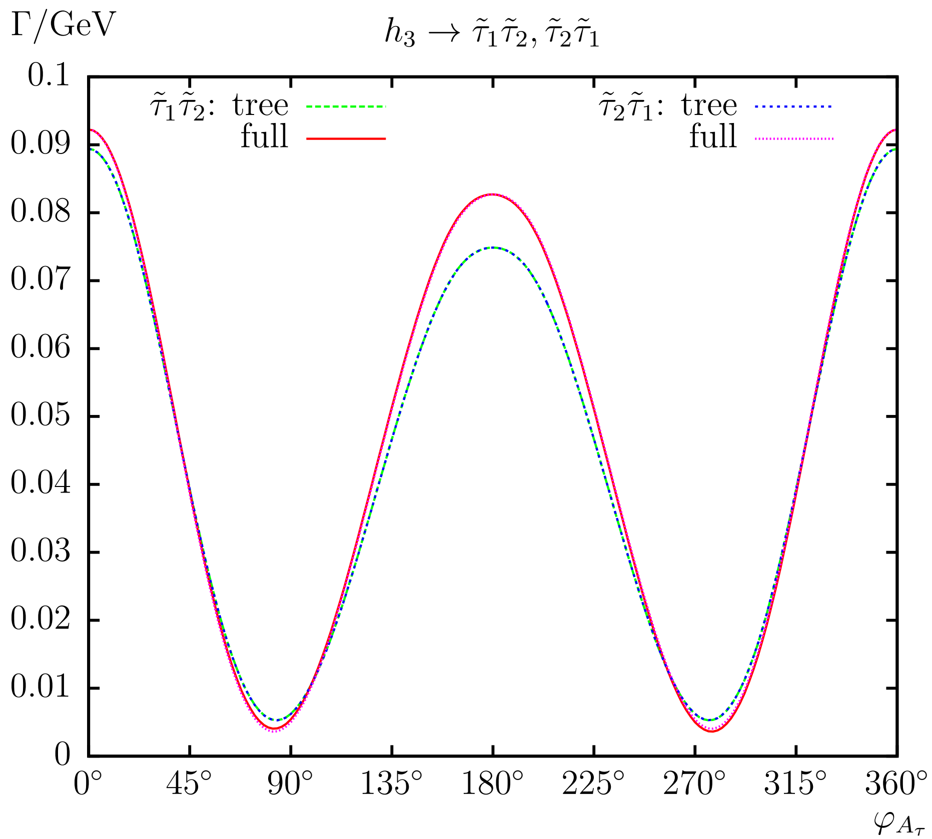


⇒ loop corrections up to $\sim$ 10%, purely EW

⇒ level crossing, thresholds, . . .

Heavy Higgs decay to staus:



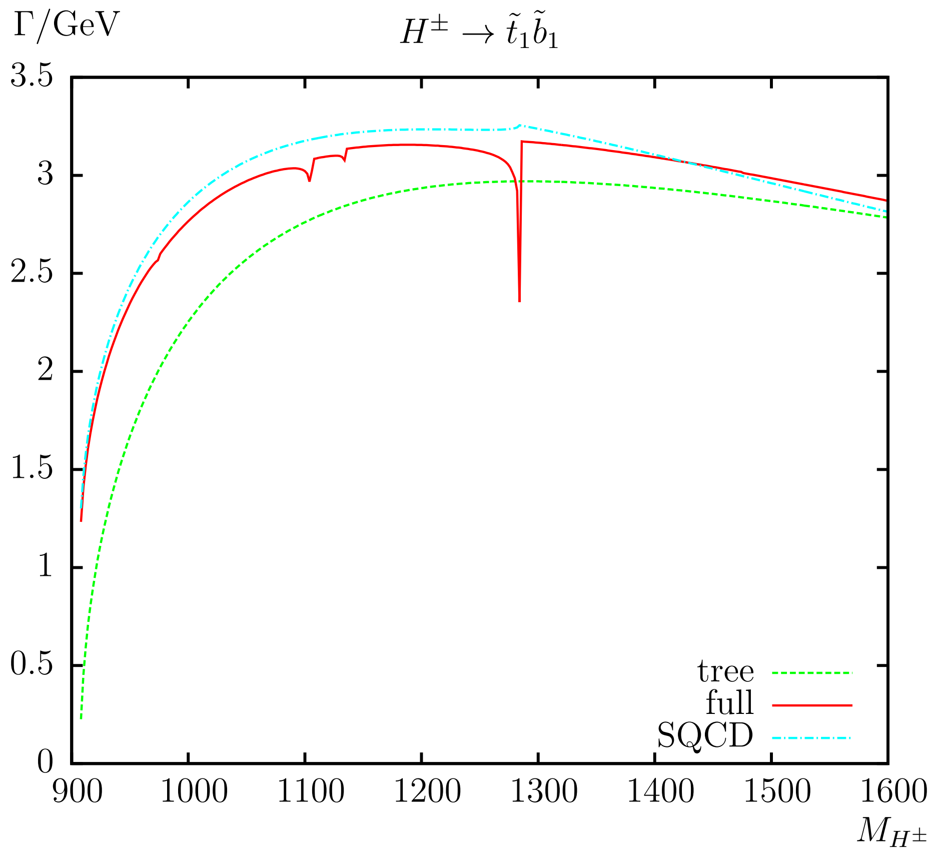


$\Rightarrow$ loop corrections up to $\sim$ 10%, purely EW

$\Rightarrow$ strong phase dependence

$\Rightarrow$ small difference between charge conjugated decays

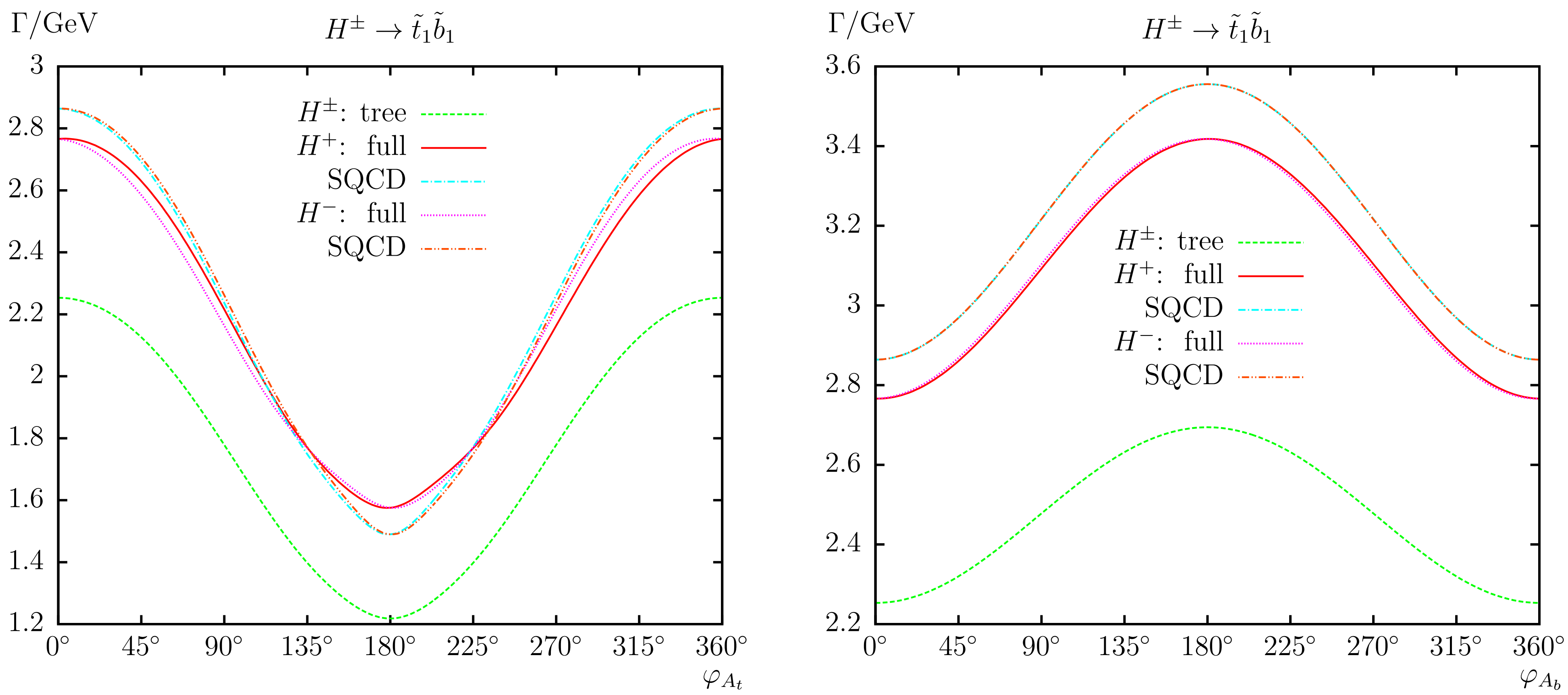
Charged Higgs decay to stop/sbottom:



$\Rightarrow$ loop corrections up to $\sim$ 30%

$\Rightarrow$ SUSY QCD not sufficient

Charged Higgs decay to stop/sbottom:



⇒ loop corrections up to $\sim 30\%$, SUSY EW important

⇒ strong phase dependence

⇒ small difference between charge conjugated decays

3E) SUSY decays to/involving also Higgs bosons

Calculated in the cMSSM full one-loop:

[*A. Bharucha, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '15*]

- stop/sbottom decays
- stau decays
- chargino decays
- neutralino decays
- gluino decays

Anything relevant missing?

$\Rightarrow$ effects always relevant for LC precision!

4. Conclusinos

- The Higgs will be explored at the LC
  SUSY will be explored at the LC

- LC precision often is in the per-cent range
  $\Rightarrow$ theory precision has to match!

  $\Rightarrow$ many corrections still missing, in particular for Higgs

- Problem in the MSSM, in particular with complex parameters:
  consistent renormalization of the whole model (simultaneously)

  $\Rightarrow$ now solved!
  $\Rightarrow$ model file available for FeynArts/FormCalc/LoopTools

  $\Rightarrow$ full one-loop calculations of any SUSY process possible

- (Updated) results available for:
  - Higgs boson masses
  - Higgs boson production cross sections
  - Higgs decays and decays to Higgs bosons
  - production of Dark Matter at the LC

- Always(?) more higher-order corr. necessary to match LC precision!